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Assessment of the actual sustainability of nuclear fission power

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ABSTRACT

This paper uses 19 criteria to assess whether nuclear fission power can be a part of sustainable development. This yes or no qualitative evaluation is due prior to ongoing marketability assessment and promotion of nuclear power by, for example, the IAEA, the IEA and the UK government. The criteria are classified into five groups. 'Planet' results demonstrate that the incompatibility of nuclear expansion with electricity efficiency and full renewable power deployment largely overshadows the carbon-free steam generation of nuclear fission. 'Prosperity' analyses show that including rolled-off costs and risks would raise bills to heights difficult to quantify due to doubts, long-term invisibility and irreversibility. 'Risks' may be catastrophic and are not insurable, while weaponry proliferation adds a further dimension. 'People' analyses reveal that some nuclear power is affordable for present generations when many costs remain unpaid; however, developing countries cannot afford the capital costs and technology intensity, and catastrophes wreak havoc on national economies, singling out exposed communities losing their habitats. 'Politics' assessments demonstrate that nuclear technocracy dominates the scene in many countries; the technocrats heavily influence policy-makers, the media, and celebrities speaking out in favor of nuclear. We identify the need for an independent global agency and for independent national nuclear regulatory institutions to safeguard the public interest.

Contents

Abbreviations: 2DS, IEA's 2 °C Scenario; CCS, Carbon Capture and Storage; UK DECC, UK Department of Energy and Climate Change; EPR, European Pressurized Reactor; GDP, gross domestic product; Gen IV, fourth generation nuclear technology; GHG, greenhouse gases; IAEA, International Atomic Energy Agency; IEA, International Energy Agency; INPRO, International Project on Innovative Nuclear Reactors and Fuel Cycles (by IAEA); IPCC, Intergovernmental Panel on Climate Change; NAIIC, Nuclear Accident Independent Investigation Commission; NPT, Non-Proliferation Treaty; NRC, Nuclear Regulatory Commission, USA; PWR, pressurized water reactor; SD, sustainable development

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1. Introduction

Addressing climate change implies decarbonizing electricity generation as the most important energy system-wide change, with a critical role for energy efficiency [1]. Renewables and nuclear power are substitutes for fossil fuel-based electricity generation. Leading institutions such as the International Energy Agency [1], the International Atomic Energy Agency [2] and the UK Department of Energy and Climate Change (DECC) [3] apply their sustainability assessment frameworks to the nuclear power option and conclude that nuclear power can form a legitimate part of a sustainable energy mix, providing certain challenges are met. This paper aims to answer the research question of whether the renewed 'policy push' for nuclear power is indeed warranted from a sustainable development point of view.

According to the IAEA [2], the concept of sustainable development encompasses three interdependent and mutually reinforcing pillars: social development, economic development and environmental protection, all linked by effective government institutions. This fourth dimension, 'Institutions and Policies', is assigned the limited task of managing the complicated industrial activities involved in nuclear systems. Linking certain principles, criteria and requirements to each of these four dimensions, the IAEA has developed an extensive framework for assessment. However, in accordance with the IAEA's mandate, this framework also serves to effect the 'responsible promotion' of nuclear power. In the IAEA framework, 'responsible' denotes accordance with the status quo in energy supply thinking and practice. This is exemplified by several 'acceptance limits' placed on the assessment criteria, such as: 'Meet regulatory standards of a specific Member State' [3, p. 84]; 'Lower consequences compared to existing facilities' [3, p. 106]; 'the generation of waste shall be kept by design to the minimum *practicable*' [3, p. 18]; 'waste shall be managed in such a way that *undue burdens* are not imposed on future generations' [3, p. 18] (our emphasis). Identifying and applying 'best current practices' is no guarantee that these practices meet the standards of sustainable development, however. The IAEA is failing to address the fundamental question of nuclear power's role in a sustainable energy future.

The IEA [1], on the other hand, situates the sustainability challenges facing nuclear power within a narrow techno-economic framing of climate change mitigation. Based on techno-economic optimization modeling, nuclear power is positioned as a vital contributor to the IEA's 2 °C Scenario (2DS). According to the IEA, however, nuclear power remains hampered by four types of impediments or 'challenges', which correspond to the usual sustainability dimensions. The technical and market challenges are considered, respectively, to be 'technological developments to improve safety, performance, lifetime management, radioactive waste handling' [1, p. 127] and 'very large capital cost to build nuclear power plants' [1, p. 127]. Meanwhile, 'supply chain capabilities, human resource availability, lack of regulatory framework' [1, p. 127] are the challenges identified at the institutional and political level. Social and environmental challenges are grouped within one category and comprise 'final disposition of waste and public concern about safety risks' [1, p. 127]. Remarkable is the blindness of IEA for the actual risks associated with nuclear power. The IEA is not addressing the risks, but the public not willing to accept the risks: 'to reach nuclear goals, countries need to make significant efforts to convince an increasingly skeptical public that nuclear power should continue to be part of the future energy mix' [1, p. 73]. Thus, the IEA approach is limited to the marketability of nuclear power, and does not extend to a consideration of its sustainability.

Finally, the UK DECC's sustainability appraisal of the national nuclear policy statement [4] emphasizes mainly environmental and health sustainability criteria, while social criteria are limited to the impact that building new nuclear power plants may have on employment opportunities and the welfare of local communities. This limited scope obviously falls short of a full sustainability appraisal of the nuclear option.

This brief review of assessment frameworks in use reveals that an extended framework for proper prior assessment of nuclear fission power's suitability for advancing sustainable development (SD) is lacking. We propose nineteen criteria for the effective assessment of nuclear fission power in terms of sustainability, which are summarized in Table 1 and discussed briefly in Section 2. The nineteen criteria are classified into five groups. Four of these groups align with the four dimensions of sustainability (planet, prosperity, people and politics), while one additional group addresses the nuclear risks pervading the other four dimensions. Following a brief discussion of the nineteen criteria (Section 2), the remainder of the paper is structured to correspond to the five groups: planet (Section 3), prosperity (Section 4), risks (Section 5), people (Section 6) and politics (Section 7). The risk group is placed in the middle of the five, because nuclear risks affect nuclear fission power's performance on the criteria of the four other groups.

2. Framework for assessing whether nuclear power can be part of sustainable development

At the Rio summit in 1992, SD was universally approved as preferred paradigm for structuring our common future [5]. Since

Table 1
Criteria for assessing whether nuclear power can be a part of sustainable development.

Dimensions	Criteria (standards on which a judgment is based). The standards are sustainability attributes to own and results to obtain by a technology.
Environmental/ecological (planet)	1. Climate change problems are relieved (mitigation and adaptation) 2. Ecological resilience of the energy system′s embedding environment is preserved 3. Exhaustible finite resources are managed in light of future substitutes 4. Electricity use efficiency and deployment of renewable electricity potentials are stimulated
Economics (prosperity)	1. All costs related to the nuclear system are identified, measured (or properly assessed), and billed to the end users of nuclear power 2. Technology evolves to higher economic efficiency: more output at reduced costs 3. Capital investments are affordable for most countries in the world 4. The electricity supply industry that results from generation technology choices is secure and reliable, with low vulnerability
Risks	1. Risks should be completely insurable, even catastrophic risks 2. Nuclear plant owners and operators are fully liable for risks, including long-term effects and impacts 3. Proliferation of technologies and know-how that can be used for nuclear weaponry is limited and reduced
Social (people)	1. Electricity bills are affordable (match the expectations of constituencies) 2. External and future costs are allocated according to the polluter pays principle and precluding displacement of problems and risks to the poor, to developing countries, and to future generations 3. Exposure to harmful pressures is low, and proper information on safety and health impacts is available 4. Global redistribution of access to natural resources and of economic wealth growth is stimulated
Governance/policy (politics)	1. A global, independent agency studies nuclear power issues and choices in terms of their longevity, uncertainties, and irreversible impacts 2. Independent and accountable nuclear regulatory institutions and processes are established and monitored publicly 3. At national/regional levels, the public interest prevails over private profit, and democratic institutions prevail over technocracy 4. At local levels, citizens can engage in debate about energy system governance, and participate in the deployment of local energy systems

energy use and supply largely determine civilization, energy technologies and systems must perform well on sustainability criteria. A number of obvious difficulties arise when crucial aspects of performance are beyond the monitoring and measuring capabilities of humankind. Before assessing the marketability of particular technologies and systems in modern industrialized or industrializing societies, it is advisable to evaluate whether nuclear power can be part of a future world in which sustainable development should prevail.

In order to carry out this evaluation, we specify nineteen criteria[1] in a framework composed of the four dimensions of SD (planet, people, prosperity, and politics) alongside an explicit analysis of the risks that pervade each of the four dimensions, particularly the social and economic dimensions. Table 1 provides an overview of the criteria. Our evaluation of nuclear power is based primarily on qualitative argumentation. Quantitative information is used when available to complement the discussion. The focus on pressurized water reactor (PWR) plants corresponds to the real importance of this fuel cycle in commercial nuclear activity and to their prevalence in proposed nuclear expansion schemes. Other nuclear technologies are not considered in the present paper. In what follows, we provide short clarifications of the nineteen criteria used for assessment, according to the sequence shown in Table 1.

2.1. Environmental/ecological: planet

1. Power supply systems will soon need to switch entirely to low-carbon resources and technologies on a global scale. The energy supply sector emitted 25.9% of worldwide anthropogenic CO_{2eq} emissions in 2004 [6]. The low-carbon options selected should also be robust enough to withstand intensifying climate change impacts such as droughts, floods, water scarcity, and storms.
2. A large-scale power station is embedded in a local environment, whose ecological resilience has to be maintained without irreversible loss. Contamination from the power plant should be contained or have no long-term effects on human spaces and other habitats.
3. Fission power involves processing uranium, of limited availability, at competitive fuel prices. If it succeeds in its revival, as IEA scenarios announce, nuclear power must offer a solution for the future scarcity of conventional uranium.
4. The consensus on the priority role of energy use efficiency and on the deployment of renewable energy potentials is unequivocal because of SD arguments. Other power supply options must prove that they support and stimulate both options and will never be an obstruction to their urgent and drastic growth.

2.2. Economics: prosperity

1. Real economic wealth is based on proper cost accounting of the products, services, activities and practices which comprise gross domestic product (GDP). It is therefore necessary to identify and quantify the external costs, benefits, risks and irreversible impacts inherent to the lifespan of a nuclear fission cycle. End users should also pay the full cost; if not, the bill will be footed by others, now or in the future.
2. Power generation options are studied in a dynamic context. We learn from past experiments and experiences in order to improve technologies and practices. A new technology is adopted for development when its future cost price is expected to decline because of learning.
3. Access to electricity is a condition for sustainable development. Examples of basic goods are light, medicine and food cooling, and the availability of driving power for productivity and comfort. The electricity supply systems of the future must be affordable for the majority of countries in the world. If they are too capital and high-tech intensive, they cannot be

[1] A criterion is "a standard on which a judgment or decision may be based" [Webster′s Collegiate Dictionary]. Here, standards are considered to be the sustainability attributes of particular power supply technologies and the results delivered by the technologies.

used worldwide and are less suitable for sustainable development.

4. Electricity supply is considered secure when users are guaranteed continuous delivery at affordable prices. It is reliable when black-outs and brown-outs happen only occasionally. The value of security and reliability depends on the end uses of electricity and on users' willingness to pay.

2.3. Risks

The risk dimension is intertwined with the four main dimensions of sustainable development, but particularly with prosperity and people. It is given separate attention here because of the high importance of the catastrophic risks associated with using and extending nuclear power.

1. All economic activities should be amenable to full-indemnity risk coverage by the global insurance and re-insurance companies. If not, costs will be transferred to others in the present or in the future.
2. Sustainable practice entails nuclear plant owners and operators being held strictly liable for the risks occasioned by their nuclear activities. The very long-term and potentially irreversible impacts also need identification and assessment.
3. The proliferation of nuclear weapon capabilities is to be limited and reduced.

2.4. Social: people

1. Affordable electricity bills pave the way to increased access to electricity-based services.
2. The 'polluter pays' principle is solid and fair when assigning environmental responsibilities. In power generation systems, the final electricity users should be liable for the full costs and risks inherent to particular technologies and plants.
3. Power plants are acceptable only when free of major hazards.
4. Core changes for sustainable development include the exploitation of other natural resources with new technologies and investments that meet the needs of developing countries.

2.5. Governance/policy: politics

1. A scientifically rooted, independent agency or panel (similar to IPCC for climate change) is necessary to study and follow up on nuclear power performance (past, present and future).
2. Controlling nuclear technology, investment, and practices requires a high level of technicality, which emphasizes the need for experts who can safeguard the public's best interests. The establishment of separate nuclear regulatory institutions is necessary. The danger of regulatory capture is high when independent concern for the public interest is lacking and supervision is weak.
3. Governments and public administration bodies looking into energy use and supply need high-level capacity and strict independence to withstand the organized interests of multinational energy corporations. Electric power companies control important public utilities, and may exert significant influence on decision-making in political circles. A case in point is the proper pricing (including levies and subsidies for accounting externalities) of energy commodities and services.
4. Electric power systems span all industrialized countries, and often have a negative impact on local communities. Distributed energy systems can provide co-benefits to local communities, especially when citizen participation is involved.

In this framework of nineteen criteria, we offer an initial review of nuclear fission power plants' performance. It is our hope that the list can be added to and enriched with more insight, evidence, information and data by our colleagues in the field.

3. Environmental/ecological (planet)

3.1. Climate change problems are relieved (mitigation and adaptation)

A major argument in the societal debate on future power options is the fact that nuclear systems cause low CO_2 emissions. In a mainly fossil fuel-driven economy, however, nuclear power does cause some greenhouse gas (GHG) emissions. The exact magnitude of these emissions is disputed, because different authors have used diverging calculation methods and assumptions for key parameters [7]. Mining, milling and transporting uranium ore differ according to ore source and quality. Energy use of enrichment by gas diffusion is higher than by centrifuging. Regions/countries employ different energy mixes. Using high-end assumptions regarding GHG emissions in construction, decommissioning and waste management, some authors obtain 288 g CO_{2eq}/kWh nuclear electricity [8]. A review of the life-cycle analysis of nuclear energy in the US found total lifetime GHG emissions of nuclear fuel cycles to be between 16 g and 55 g CO_{2eq}/kWh [9], while a more recent review finds an average of 10 g CO_{2eq}/kWh for several regions worldwide [10]. With GHG emissions several times lower than fossil fuel-generated kWh, nuclear power life-cycle emissions are correlated with the carbon intensity of the energy economies they are embedded in (Fig. 1).

Of higher interest is the contribution of nuclear plants to the full decarbonization of electricity systems. Nuclear plants provide base-load capacity, complemented by – today fossil fuel-driven – intermediate and peak load supplies. Most of the renewable energy supplies of the future are not suited to load following, but compete with nuclear supplies for priority ranking in the merit order. In other words, they compete to deliver base-load electricity. Dam hydro and bio energy fueled plants can follow fluctuating loads, but will differ in design, size and place in supporting either nuclear bulk power or distributed flows of variable renewable power (wind, solar, run-of-the-river hydro). The existing incompatibility between nuclear and renewable power at the operational level in countries such as Spain, Germany and Belgium demands clarity at the level of strategic investment decisions: it is either nuclear power or renewable electricity [12].

Robust electricity systems can deliver power for adaptation initiatives and measures to reduce the vulnerability of natural and human systems to actual or expected climate change effects. With about 3 m^3 cooling water/MWh_e produced, nuclear plants' cooling water consumption is higher than that of fossil-fuel plants [13]. Throughout the world, new nuclear plants and existing plants increasingly face cooling water scarcity, a situation that is likely to be aggravated by climate change [14]. Hence nuclear plants are already sited in coastal or estuarine locations, making them vulnerable to flooding and extreme events that climate change may occasion [15], out of the hands of nuclear power designers. The Fukushima disaster reveals how powerless human operators are when nuclear systems escape full, continuous control. Instead of helping to address the impacts of the tsunami, the devastated nuclear power plants strongly aggravated the emergency relief in the province.

3.2. Ecological resilience of the energy system's embedding environment is preserved

Surface or underground mining and the processing of uranium ore can substantially damage surrounding ecosystems and

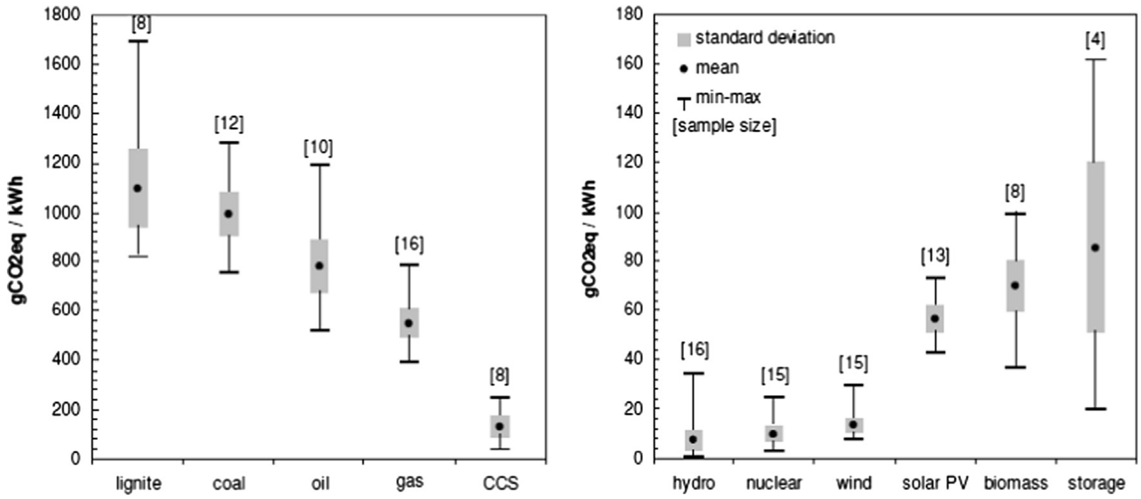


Fig. 1. Life-cycle GHG emissions for selected power plants.
Source: [11].

waterways [16,17]. Adequate coverage of the mining tailings and restoration of the landscape to its original state after the termination of mining activities can attenuate the environmental impacts. As regards the power generation stage, the UK National Policy Statement for Nuclear Power Generation [4] also covers standard environmental themes such as air quality, soil, water, and landscape. It concludes that under controlled[2] operation, nuclear power plants cause controllable externalities. However, the routine discharging of nuclear isotopes at reprocessing plants and the adverse effects on local air and aquatic ecosystems caused by noble gas emissions and thermal pollution merit more scrutiny [17].

The back end of the fuel cycle is dominated by the containment of spent fuel rods and waste from decommissioned nuclear power facilities. Safe and secure long-term storage of nuclear waste remains unresolved, with persisting hazards over almost eternal time spans. The half-life of spent fuel is about 25,000 years, with radioactivity from long-lived fission products lasting millions of years [18]. Most nuclear experts believe that there exist handling and storing techniques that meet the safety requirements applicable in various countries, though they also point out a number of technical uncertainties that need further study [19].

Finally, when major nuclear plant accidents occur significant land areas become unsuitable for human habitation (e.g. Chernobyl, Fukushima). Advocates of nuclear power draw attention to the survival of natural flora and fauna in zones contaminated by radioactive materials and precluding human access. However, this is presumably not the pursued type of ecological resilience we are aiming to achieve.

3.3. Exhaustible finite resources are managed in light of future substitutes

Economic reserves of exploitable-grade uranium ore for once-through fission processes are limited, and expected to be depleted in nuclear power growth scenarios by approximately 2075. ‘Assuming that only 6.3 Mt U of conventional resources are available, fast breeder reactors will provide around 60% of nuclear generation by 2075. Without fast breeder reactors and relying solely on once-through fuel cycles, nuclear generation would have to fall to around 1400 TWh in 2075’ [1]. The IEA’s 2DS base scenario projects a 19% supply share (7918 TWh) for nuclear power in 2050 [1, p. 384], while an extension of this program leads IEA to an estimation of 11,000 TWh nuclear power generation by 2075 (still 19% of supply share) [1, p. 521]. This situation is not comfortable for nuclear power. On the one hand, nuclear vendors’ only immediately marketable product for keeping the business going is the oversized PWR. If sales were successful, the world would be populated with obsolete technology, exhausting the economic uranium reserves and likely causing price hikes in nuclear fuel. On the other hand, it is an adventurous bet that commercial fast breeder technology will be available by 2075. The annals on the first breeder wave are not particularly promising: Fermi (USA), Phoenix and Superphoenix (France), Kalkar (Germany, Belgium and the Netherlands), Monju (Japan) and Dounreay (UK). Vendors are not investing in breeder research or prototypes and look to public research institutes and budgets to do so. After 50 years of absorbing the major shares of public R&D energy budgets, the return on this investment ought to be quantified. The likelihood of achieving breakthroughs in this technology in the next few decades should then be investigated.

3.4. Stimulates energy efficiency and deployment of renewable energy potentials

In order to decarbonize the electricity sector, green roadmaps rely exclusively on energy efficiency and renewable power sources. The feasibility of effecting a full transition to renewable energy has been confirmed by the IPCC [20]. The IEA [1] also considers energy efficiency and renewable energy to be critical, representing 60% of the decarbonizing efforts. The IEA also assigns significant roles to Carbon Capture and Storage (CCS) and nuclear power, juxtaposing all feasible technologies to fill the full reduction pie. This usual portfolio approach is justified by one-liners about there being no ‘silver bullets’ and about not ‘putting all our eggs in one basket’. The challenge of keeping nuclear power generation expenses affordable is addressed by planning series of ultra large-scale plants. But such plants are not flexible and not compatible with energy end-use efficiency and flow renewable sources like wind and solar [12]. Since the 1950s, nuclear power has received VIP treatment, sidelining and overtaking the development and deployment of sustainable alternatives. Now, efficiency and renewable energy merit priority roles and adequate support in effective policies and with proper price signals in the electricity business.

[2] The UK administration assumes that nuclear systems remain under control when they follow imposed regulations; see e.g. [4, p. xiii]: “Due to the robustness of the [UK's] regulatory regime, there is a very low probability of an unintended release of radiation and routine radioactive discharges from new nuclear power stations will need to be within legally authorized limits”.

4. Economics (prosperity)

4.1. All costs related to the nuclear system are identified, measured (or properly assessed), and billed to the end users of nuclear power

Evaluating nuclear power economics depends on the completeness of cost accounting and the imputation of all costs in prices [21]. Unpaid external costs and risks, unwarranted (often hidden) subsidies, monopoly power, unclear muddling of public and private interests, and of civil and military affairs, are all factors that may create wide gaps between the stated and actual costs of nuclear projects. Comparing the costs of nuclear power generation to those of other technologies, then, is a precarious activity. Existing comparisons (e.g. [22,23]) mostly include only those costs related to the generation phase in the life cycle: decommissioning and external costs are usually ignored or only partially incorporated. Furthermore, the costs of generating electricity appear to be largely country-specific: it is perilous to generalize findings on generation costs [22].

The Cold War divided the world, including its existing nuclear programs. The nuclear energy industry behind the Iron Curtain relied on technology and expertise from the Soviet Union and was supported by defense-related spending. The history of the nuclear power industry is characterized by the benefits gained from a vast range of preferential government subsidies [24], strong political support and favorable liability regimes [25]. Additionally, in socialist and capitalist economies alike, the supply of electricity was handled by regulated monopolies, allowing for expenditures to be shifted entirely to electricity end users [26]. Initially, the aim was to allow the nuclear industry to grow, but after 50 years of support the question is now whether continuing subsidies are warranted [25]. The cost rankings of generating technologies are considered to be dependent on the availability of federal incentives [27]. Koplow [24] finds that the nuclear power industry was only able to promote itself as a low-cost power supplier because of previous government subsidies and write-offs. Loan guarantees hide the technology's true costs to the economy, but also to the customers themselves, encouraging wasteful consumption practices [28,26]. Similarly, the risks related to the operation of nuclear power plants and to waste handling are major cost factors, but these are largely rolled off on society and on future parties. Section 5 offers a more detailed discussion of the risk aspects.

4.2. Technology evolves to higher economic efficiency: more output at reduced costs

Unit costs mostly decline as technologies are increasingly diffused and applied, an effect mostly understood as 'learning-by-doing' and reflected in the experience curve for every doubling of cumulative production [29]. The specific investment costs of nuclear plants increased in the 1970s [30]; recent studies confirm this trend has continued since [31]. The cost escalation of reactor construction [32,33] is often explained by more stringent safety requirements [31]. This factor may make nuclear learning effects less visible compared to (fossil fuel or renewable power) technologies with fewer safety concerns [29]. Cost escalations may also be caused by the limited sharing of experience, since nuclear plants are designed and built on an individual basis according to local conditions with long lead times in planning processes, construction, and commissioning [31]. The complex nature of nuclear reactors and their site-specific requirements obstruct full standardization and limit learning effects [34].

Grübler [35] analyzed the French PWR program, widely considered the most successful nuclear expansion and scale-up experience because of the institutional conditions (central planning) and regulatory clarity. However, this program's specific investment costs increased by 5–6% per annum, i.e. the learning effect has been negative. It seems that nuclear technology costs are not characterized by the learning-by-doing effects we might anticipate, but rather by 'forgetting-by-not-doing' or even worse: 'forgetting-by-doing'. Opportunities for learning are structured by actors and institutional settings, but they are conditional on the technology itself. Nuclear cost escalations are caused by increasing safety demands and by the nature of the technology itself: large-scale, lumpy, and requiring a formidable ability to manage complicated processes in both construction and operation. The latter supersede standard cost-lowering drivers such as standardization, large series and quasi-identical experiences. It could be that nuclear technology complexity inevitably rises with increased application ('doing'), leading to inherent cost escalation trends that limit or reverse the learning (cost reduction) possibilities [35]. Grübler's findings are in line with observed cost overruns on two ongoing European pressurized reactor (EPR) constructions in Europe. Between 2005 and 2013, the French Flamanville-3 reactor went up in capital cost from €3.3 billion to €8 billion, with start-up delayed from 2013 until the end of 2016 [36]. Similarly, the Olkiluoto-3 EPR in Finland had planned building expenditures of €3.2 billion, later recalculated to €6 billion [37], with AREVA mentioning a price similar to that of Flamanville-3 [38]. Planned for 2009, the start of production is now estimated for early 2016 [39,40]. Problems with large reactors shift attention to small ones, but Makhijani and Boyd [41] expect diseconomies by downscaling because nuclear reactors are not suitable for mass-production. This inevitably rekindles the discussion about the affordability of nuclear power, at any scale.

4.3. Capital investments are affordable for most countries in the world

Some promote nuclear power as the pre-eminent provider of economic development and industrial progress in developing countries hampered in catching the development train by a lack of adequate electricity supplies [42,43]. The IAEA identified the need for national institutions and infrastructure as a main impediment to nuclear expansion in developing countries: planning and decision-making capabilities, organizational structures, electricity grid size and structure, qualified manpower, industrial support and financing [42].

Jewell [44] analyzes the capacities and motivations behind the development of national nuclear power programs based on historical evidence. She finds that countries with established nuclear programs are typically in the mid- to high-income group and in politically stable economies with high government effectiveness. Countries with privately owned nuclear facilities, in particular, fall into the high-income group.

A country with a GDP below US$50 billion is unlikely to buy a nuclear reactor costing several billion dollars, and 10 GW electric grids is the minimum to accommodate a large nuclear reactor. Of the 50 developing countries, which have expressed an interest to the IAEA in acquiring a first nuclear power plant, only 16 meet the criteria [45]. Today, only 30 countries have one or more nuclear power plants in operation. With the exception of Armenia, which has a 1980 USSR plant, all belong to the richest half of the world's nations [46,47]. Similarly, the 68 plants currently under construction are located in countries that achieved a certain level of development, the majority having already built nuclear reactors in the past [48].

As marketability factors of nuclear power, the IAEA [2] rightly recognizes institutions, policies and a country's level of infrastructure development, but should not conclude that nuclear energy is part of a country's future energy mix, let alone suggest that nuclear deployment could pave the way to development. Such

countries have the means to choose less costly electricity generation technologies that fit their still-growing network capacities better. Scarce governmental resources in developing countries face multiple demands from other important societal and economic fields [45].

4.4. The electricity supply industry that results from generation technology choices is secure and reliable, with low vulnerability

The security of supply involves several aspects of varying relevance depending on the scope and perspective of the assessment. Kruyt et al. [49] find that contemporary energy security definitions relate to the availability of energy (geological existence), as well as its accessibility (related to geopolitical elements), affordability (economics) and acceptability (environmental and societal). Security is also characterized by the time dimension and by changing contexts caused by developments worldwide. For a given country, secure energy means 'having enough' energy supply guaranteed at affordable prices for its population as consumers and producers of goods and services, not interrupted by foreign actors. Nuclear power programs are highly dependent on limited uranium sources [1], several of which are located in politically unstable regions. Technology and related services are to be obtained from nuclear-pioneer industrialized countries. Aspects related to the non-affordability and non-acceptability of nuclear power are discussed in Sections 3, 4 and 7.

Reliable energy equals energy is delivered at time and place required by end users, through adequate systems with few failures. Reliability is often expressed in terms of a subset measure, availability, as the share of time the supply is deliverable. The reliability of nuclear power has been high in several countries (Finland, Romania, South Korea, Switzerland, China and Belgium) [50]. Some nuclear power plants have been unavailable for actual electricity production during significant periods of their lifetime, however. In the United States, no less than 21% of plants have been permanently and prematurely closed for safety or cost reasons, while an additional 27% failed at least once a year or more frequently [51]. Furthermore, an aging worldwide reactor fleet might be expected to become less reliable as time goes on (Belgian cracks, Fukushima). Perrow (1984) observes that no amount of lessons learned, regulatory requirements or precautionary principles can guard against the myriad of things that can go wrong in complex high-tech systems such as nuclear energy systems [52].

Large-scale plants have a significant impact on grids, particularly on smaller grids; the largest plant in a power system is permanently backed-up by spinning reserves. Interaction with variable renewable supplies is expected to cause escalating frictions, recently confirmed by Spanish, German and Belgian experiences (Section 3.1).

Questionable safety and high vulnerability affect electricity supply. Low vulnerability can be viewed as robustness to human and natural interferences in various degrees, from vandalism to terrorism and warfare, and from lightning to hurricanes and earthquakes. A level of zero vulnerability is practically unattainable for every technology prone to some kind of incident. Systems such as nuclear reactors are interactively complex and tightly coupled: an incident occurring in this setting may seem trivial at the outset but can cascade in unpredictable ways [52]. Incidents should be judged in terms of the risks they may trigger, particularly in the case of nuclear reactors (Section 5). Besides, the nature of nuclear power plants makes them a tempting target for criminal attacks: as a symbol of technological development, an attack would yield an immediate effect on electricity generation, plus extensive long-term economic and health effects, and impact on other countries as they may reconsider their nuclear programs [53].

Threats to nuclear supply security also emerge from the risks of proliferation that is inextricably linked to nuclear power diffusion (Section 5.3). The Fukushima accident revealed human unpreparedness for natural disasters, and for the cascade of events once problems begun. Japan had not fully considered the effects of seismic activity on its east coast, where large tsunamis have occurred repeatedly in the past [17]. TEPCO′s initial confusion and initial hesitation to take action demonstrated both the operator′s and the government′s unpreparedness for disaster [54].

5. Risks

The risks related to nuclear energy systems have a crucial impact on these systems' acceptability in the domain of the four SD dimensions (Sections 3, 4, 6 and 7). Like for nuclear advocates, the IEA′s primary goal is reducing public concern about nuclear risks, rather than addressing the material risk issues. The UK administration behaves as it has regulated nuclear risks down to levels that should be accepted by the population of the UK and by neighboring countries [4,55].

5.1. Risks should be completely insurable, even catastrophic risks

The strict application of the precautionary principle [56] would necessitate the immediate phase-out of nuclear power [12]. Insurance markets adopt a more reduced, economically minded approach to risk treatment. Since centuries, the insurance sector is the pre-eminent institution for balancing the risks perceived by individuals, organizations, and companies. Nuclear liability insurance provides limited, ex-post compensation for incurred losses [57]. However, what is needed is full indemnity insurance entailing full compensation of losses in the case of an incident. Full indemnity insurance is presumably acceptable as an adequate reflection of the precautionary 'polluter pays' principle when ex-ante estimation of impacts caused by adverse events is deemed inaccurate. Nuclear operators should provide sufficient funds and guarantees to offset and mitigate the full cost of the effects and impacts of their activities [12], which would entail full indemnity insurance as a minimum. In that case, the external (financial) costs associated with a nuclear accident would be largely internalized [25,58].

The reality is rather different, however. In the first years of nuclear power supply, insurance companies were quick to recognize the problems arising from the sector′s unknown hazards with respect to both material damage and liability to the public, with very large values exposed to risk and little risk spreading when there were too few plants [59]. In the meantime, several hundreds of nuclear plants have become operational, but insurance companies continue to state that their underwriting capacities are not large enough. First, the assessment of expected losses often fails, requiring excessively large provisions, even if the statistically expected loss is considered small. Second, the 'law of large numbers' is invalid. Insurers refuse to provide full indemnity coverage of nuclear power plants and choose instead to allocate a small percentage of their portfolio to limited nuclear liabilities [57].

Recall that when considering levels of cautiousness, insurance is on a lower level than precaution. Non-insurable activities should not be permitted. Yet, by following the rules of the market as set by the best-informed parties, namely the global insurance and re-insurance companies, it does preclude the expansion of nuclear power. It appears that insurance companies are unwilling to jeopardize their own survival, indicating that the economic and societal risks of nuclear power are of real concern [12]. This fact is

a refutation of arguments in which nuclear power is presented as a low-risk energy source.

5.2. Nuclear plant owners and operators are fully liable for risks, including long-term effects and impacts

Nuclear subsidies indicate that nuclear operators were never economically responsible for the full costs and risks of their operations [24]. The liability of the operator is limited and the remaining costs are (largely) taken on by the state, which has a negative effect on incentives, compensation and efficiency [25]. Government guarantees disturb the basic function of credit markets, distinguishing credit risks and assigning appropriate risk premiums, and thus disturbing the credit markets' allocation of resources [28]. This practice distorts market choices that would otherwise favor less risky investments [24].

In the phase of demonstrating new technologies, support from public authorities for lowering inventor risks is appropriate as compensation for external benefits. However, providing subsidies to commercial plants implies a shift of construction costs and operating risks from investors to taxpayers and ratepayers [24,26]. The financial gains of nuclear power are privatized, with private investors benefitting when the plants are financially successful, while the risks and potentially severe losses are placed on society [24].

Nuclear advocates proclaim that nuclear power is a low-cost, low-risk solution, but major externality costs are not taken into account and government subsidizing obscures the real costs of nuclear energy. The financial and risk burdens of nuclear power are ultimately shouldered by citizens and the treasury.

5.3. Proliferation of technologies and know-how that can be used for nuclear weaponry is limited and reduced

The link between civilian nuclear power and nuclear weapons proliferation has been a matter of debate since the dawn of the nuclear age. The IAEA-governed non-proliferation regime, with nuclear safeguards and the 1968 Nuclear Non-Proliferation Treaty (NPT), has failed to preclude proliferation. India, Israel and Pakistan remained outside of the NPT in order to develop nuclear weapons. Two ambiguities impact the effectiveness of the present safeguard regime. First, the IAEA, which is responsible for inspections, has a double mission: it promotes the peaceful application of nuclear technology and also ensures that signatories of the NPT do not develop military applications. However, North Korea signed the NPT and acquired nuclear technology with IAEA support, only to subsequently withdraw from the NPT and develop nuclear weapons. The second NPT ambiguity is the disparity between the nuclear weapon 'haves' and 'have-nots'. States that signed the treaty declared their intention not to develop nuclear weapons, while the five official nuclear weapon states (USA, USSR, UK, China and France) promised to reduce their nuclear arsenals (though no deadline was set). The pledges remained dead letter for a long time; some reduction has been achieved, but none of the official nuclear weapon states have demonstrated real intent to cut back significantly. This situation could be an incentive for states feeling threatened by one of the nuclear weapon states to develop their own nuclear weapon capabilities, as the nuclear armed powers argue is the case for Iran (a signatory of the NPT).

If nuclear power were to become widespread around the globe (especially 'dual use technologies' such as fuel enrichment and reprocessing), access to nuclear technology and also to nuclear weaponry would be easier and more direct. This situation would put the already strained NPT regime under even more pressure.

6. Social (people)

6.1. Electricity bills are affordable (match the expectations of constituencies)

Power generation costs contribute to electricity bills, in addition to transmission and distribution costs, profits, taxes and levies. Our assessment in Sections 4.2 and 4.3 shows that the costs of nuclear power generation charged to the consumer can be kept reasonably low under specific conditions. When societies are prone to accept particular kinds and levels of risk, and the wheel of fortune is benevolent, large amounts of nuclear power can be generated at affordable expenses (e.g. in France in recent decades). However, nuclear accounts neglect the externality costs of major accidents (by limiting the liability of owners and operators) and of the eternal concern for high-level waste (including the likelihood that funds set aside for this purpose will not be available when needed). Existing instruments for gauging and assessing such externality costs fall short [58,60]. To date, the absence of knowledge and understanding has been used as a validation of the idea that costs are low. Logically, however, this lack of knowledge is an extra argument for adopting precautionary attitudes and policies when assessing the future affordability of nuclear programs.

6.2. External and future costs are allocated according to the 'polluter pays' principle and precluding displacement of problems and risks to the poor, to developing countries, and to future generations

Nuclear power poses significant challenges in terms of intra- and inter-generational ethics. These challenges are most salient with regard to nuclear waste creation and disposal. Intra-generational problems are caused, for example, by the siting choices of nuclear waste facilities. Very likely candidates for future waste management activities are sites and their adjacent communities, which already host nuclear facilities and are labeled 'nuclear oases' by Blowers [61]. Nuclear oases are peripheral communities, and examples include Sellafield in England, Hanford in the United States, Dounreay in Scotland and Cap de la Hague in France. Characterized by remoteness, marginality and powerlessness and/or previous environmental degradation, such communities exhibit 'a relatively stable locational pattern as a declining industry is resisted in all but the nuclear oases' [61]. Similarly, the impacts of careless mining and mine tailings are imposed on developing countries, with the most severe effects felt at the mining sites and neighboring communities.

Inter-generational ethical challenges are related to the loss of human habitats following major accidents and to the long-lived nature of radioactive waste. The current pressure to support new nuclear developments emphasizes contemporary needs, i.e. the production of electricity, investment in jobs and security of supply [62]. In such circumstances, societies answer affirmatively to the ethical question of whether potential radioactive pollution arising in the distant future could be justified. However, no sufficient moral grounds exist for imposing burdens on future generations without their consent (which is impossible, in any case) and without compensation. It is striking how little attention contemporary societies are paying to the social and economic conditions that surface in the future, and which may have a huge impact on the risks of nuclear waste management. Long-lasting socioeconomic stability and institutional continuity are necessary for the proper management of nuclear sites, but these elements are both hard to predict and impossible to guarantee.

6.3. Exposure to harmful pressure is low, and proper information on safety and health impacts is available

With regard to impacts on present generations, the highest potential environmental and health risks associated with the use

of nuclear fission power are those caused by major accidents at nuclear facilities. No matter how small the probability calculated by probabilistic risk assessments, operational nuclear facilities involve real hazards. Most visceral in public memory are the nuclear power plant accident at Three Miles Island (USA 1979) and the disasters of Chernobyl (Ukraine 1986) and Fukushima (Japan 2011). Drafting a comprehensive catalog of all of the impacts of such serious nuclear accidents, and evaluating them (e.g. lost output from evacuated industrial sites, nuclear reactor shutdowns worldwide, psychological damage resulting from evacuations, etc.), would require a far broader approach than the narrow engineering-economic methodology allows. When attempting to put nuclear risks into perspective, nuclear proponents argue firstly that large-scale accidents such as Chernobyl and Fukushima are the result of unique, unrepeatable sequences of events (for which the global nuclear industry can hardly be blamed); and secondly that lessons from incidents and accidents are taken into account in new safety designs and practices where relevant [62]. However, the Fukushima disaster highlights a number of important areas in which lessons from previous accidents were not carried over [54]:

- Both the Japanese regulator and the power plant operator (TEPCO) failed to take into account two perfectly foreseeable causes of accidents (tsunamis and earthquakes). The Fukushima Nuclear Accident Independent Investigation Commission (NAIIC) has labeled the Fukushima accident 'manmade' and speaks of 'collusion between government, the regulator and TEPCO' [54, p. 16]. Nuclear regulators and nuclear power plant operators worldwide should show greater willingness and imagination in addressing improbable (but not impossible) causes of nuclear accidents.
- Hydrogen explosions resulting from the reaction of steam with the zirconium cladding of fuel elements represent a real danger in a loss-of-coolant situation; hydrogen re-combiners can limit this risk to some extent but were not installed in the Fukushima reactors despite recommendations following the Three Mile Island accident, which showed hydrogen formation to be ten times higher than predicted [18,63].
- The Fukushima disaster demonstrates the risks of common-mode failures (destruction of the entire site's emergency diesel power generators, seawater cooling pumps and external power supply) incurred by locating the emergency facilities within the 'paralysis radius' of a reactor accident, and multiplied by installing several reactors on one site. This is highly relevant to the existing reactor fleet and to future nuclear programs dependent on constructing new reactors on existing sites (e.g. UK plans).
- Fukushima also confirmed the porosity of impact circles around reactors: depending on weather circumstances, living and industrial areas beyond the 30 km radius circle are exposed to high levels of radiation.

Hirsch et al. [53] provide a comprehensive overview of nuclear reactor hazards, pointing out many potential accident causes such as negligence, poor design, natural disasters, terrorism (both as a prime target, but also for theft and the creation of dirty bombs), and the threat of multiplication possible with nuclear energy in operation during both international wartime and domestic conflicts.

6.4. Global redistribution of access to natural resources and of economic wealth growth is stimulated

In Section 4.3 it is shown that nuclear power generation is mostly reserved for more industrialized and wealthy nations. Therefore, nuclear power is not suitable for redistributing direct access to resources and related economic growth. However, the indirect impact of protracted betting on nuclear power by the industrialized world is even more serious. The organizational and financial capabilities spent on nuclear power deprive electricity efficiency and renewable electricity of valuable R&D and deployment opportunities. The electricity sector's full transition process is disrupted and delayed. This in turn has negative impacts on developing countries, many of which possess huge renewable energy resources but lack affordable technologies for exploiting them. A deliberate, univocal and exclusive choice in favor of electricity efficiency and renewable electricity would provide the highest chances of achieving a rapid supply of affordable solutions for poor countries. Further spending on nuclear power expansion thus impedes the development and deployment of electricity efficiency and renewable supplies [12].

7. Governance/policy (politics)

7.1. A global, independent agency studies nuclear power issues and choices in terms of their longevity, uncertainties, and irreversible impacts

Historically, the development of nuclear power programs has been driven and justified by nation-building interests, often overlapping with a desire to build nuclear weapons capability. Jasanoff and Kim [64] speak of 'socio-technical imaginaries' to explore the close link between the development of nuclear power and the development of national narratives. In short, powerful images help to enforce the image of power. In view of this historical observation, it comes as no surprise that the world's most powerful nation states are unwilling to submit the justification of a technological program, seen as vital to their national interests, to independent deliberation on a global level. For instance, in the two decades of post-Rio global climate change negotiations, the nuclear issue has been consistently delegated to member state level, in contrast to the way in which multilateral negotiations were carried out with the aim of affecting fossil fuel and renewable energy policies. International organizations such as the IEA and the IAEA have implicitly limited their evaluations of nuclear power to the question of 'marketability', i.e. what governments should do to make nuclear power acceptable to 'the market' following a decision to rely on nuclear power generation [4].

Whenever aspects of the nuclear fuel cycle have been made subject to international or transnational regulations (e.g. the EURATOM treaty and its subsequent implementation; the NPT; the Paris Treaty on nuclear liability), powerful nuclear states have imposed their interests (see also Section 5.2 on limited liability; Section 5.3 on the NPT). For instance, the initial drive and proactive approach of the EURATOM treaty towards common safety and waste regulations in the public interest is reduced now to a conglomerate of national initiatives, without global ambitions for common safety criteria and guaranteed waste funding, or common rules for the quality control of waste packages at the EU level. International forums on alternative nuclear fuel cycles (Gen IV) present new generations of nuclear technology as sustainable contributions to future energy systems based on optimized resource use, long-term waste reduction, proliferation resistance and safety improvements. While the related R&D absorbs huge budgets, the challenges of increased trans-boundary shipment of nuclear materials, and of security and safety issues linked to breeder technology, have not been considered sufficiently in terms of strengthening global regulatory institutions. The nuclear discourse has opportunistically adopted certain elements of sustainability, such as the climate change issue. Unbiased, comparative

sustainability assessments of the Gen IV strategy are lacking. Experts and institutions in the nuclear sector, in particular, will face cultural difficulties during the transition towards sustainability and there is a significant lack of independent expertise [65]. Expert bias in the nuclear sector pre-empts independence, thus annihilating the relevance of what are commonly presented as 'independent' sustainability assessments.

7.2. Independent and accountable nuclear regulatory institutions and processes are established and monitored publicly

Nuclear safety regulators and waste management organizations are specialized public institutions and have significant discretionary powers. But can and do these discretionary powers yield sufficiently independent results for safeguarding the public interest against private profit maximization and/or particular political interests. Here, the distinction between formal and informal independence is essential. Formal independence can be guaranteed by means of specific provisions, such as rules for the appointment and function of the chairperson and management board; financing and organization (source of budget, control of human resources); relationships with elected officials (e.g. formal accountability obligations, power to overturn decisions); and assigning the scope of regulatory competences (in terms of rulemaking, monitoring and sanctioning). Informal dependence weakens nuclear regulatory institutions by, for example, inadequate budgets, hidden influence exerted by private actors and politicians, 'revolving door' positions, partisanship in appointing leading staff, and so on. Evidence on informal dependence is mostly but revealed by analyzing nuclear incidents and accidents.

The Fukushima accident (Section 6.3) again highlighted the dangers of 'regulatory capture' by the major power company TEPCO under conditions of centralized control and planning with limited room for dissent [54]. Anecdotal evidence from former 'insiders' has been voiced, for instance by Gregory Jaczko, former chairman of the US nuclear regulatory commission (NRC), who left after a dispute over licensing the construction of a new nuclear power plant in the US (which he opposed). In a recent interview [66], he asserted that:

- The most significant problem with the NRC remains the heavy influence that the industry has in selecting the members of the commission. It is a very political process;
- Few commissioners ever get onto the commission without endorsement from the industry;
- The industry has a very strong influence over commission members;
- It would be virtually impossible for someone who is publicly skeptical of nuclear power ever to be confirmed as a commissioner on the NRC;
- The culture that exists now is one of not wanting to have the NRC involved, wanting the licensees themselves to do more and wishing the NRC to have a lesser degree of oversight.

The role of sufficiently independent and strong regulators in a sustainable energy future needs to be stressed and actively safeguarded against the inherent tendencies of 'closed-circle decision-making' on nuclear issues.

7.3. At national/regional levels, the public interest prevails over private profit, and democratic institutions prevail over technocracy

The relationship between democratic decision-making and technology development was addressed by Winner's question: 'do artefacts have politics?' [67]. In other words, do technologies shape or determine political action? Winner inspired science and technology scholars to explore the social and political relations contained within various societies making use of nuclear power programs. Grove-White et al. [68] coined the term 'social constitution' to capture the typical patterns of socio-political relationships corresponding to the introduction of a particular technology. Researching different country contexts, Rochlin [69] revealed seven salient attributes of the 'social constitution' of successful nuclear power programs (most notably in France):

1. A political consensus to assign discretionary power over energy choices to a technical-scientific elite operating within a centralized, hierarchical and non-participatory monitoring and planning system (with respect to investment and site selection);
2. The absence or marginalization of expertise contradicting the official elite position, for steering government choices;
3. The absence of institutional mechanisms which permit 'outsiders' to participate in the formal planning process;
4. The government's support of the standardization of reactor designs; series ordering of power plants was encouraged by the government;
5. The willingness of utilities to accept the standardization of reactor suppliers and technical equipment rather than opting for diversity and competition among designs;
6. The willingness of governments to accept unique and privileged liability burdens (Section 5.2);
7. The presence of an integrated electricity network specifically developed and managed for the integration of large production units (such as nuclear power plants).

These seven attributes leave little room for democratic political agency, typically characterized by inherent conflicts, debates and reversals in policy processes. An interesting policy question, then, concerns the extent to which conditions of centralized control and planning with limited room for dissent can and will be reproduced for future nuclear programs. In particular, the need for more extensive public involvement in decision-making on science and technology is gradually being recognized by the nuclear sector [70]. Stakeholder involvement is now being advocated as an integral part of decision making, and is widely recommended at the national and supra-national levels for all aspects of the nuclear fuel cycle: uranium mining [71], radioactive waste management [72], location of new nuclear power plants [73], emergency situations [74] and rehabilitation of contaminated territories [75].

Whether calls for more participation serve as rhetorical tools or as a 'politics of talk' in high-level policy documents – rather than being characteristic of a wider philosophical sea change in nuclear sector practices – remains a matter of debate, however, requiring detailed empirical investigation of actual cases of participatory engagement in nuclear policy making. In any case, a watchful eye should be kept on the real purposes of the participation process. Since public acceptance issues are considered largely as a barrier to be overcome in nuclear power [2], one should be careful not to confuse real attempts to increase public involvement with charm offensives and promotion. Because of the intimate connection between finding a solution for high-level waste and the future prospects of nuclear power, it is no coincidence that the nuclear participatory effort focuses intensely on finding host communities for nuclear waste management sites [76]. A special issue of the *Journal of Integrative Environmental Sciences* [77] adopts a critical stance on participatory radioactive waste governance in the UK, Sweden, Finland and France, arguing that there is a constant danger of deliberative engagement being used instrumentally to endorse incumbent policy rather than to develop sustainable policy. The paper demonstrates the fragility of deliberative

approaches when faced with strong powers able to steer policy outcomes.

7.4. At local levels, citizens can engage in debate about energy system governance, and participate in the deployment of local energy systems

National nuclear systems are, and must be, managed by centralized planning bodies and authorities, complemented by international control in order to minimize proliferation and terrorism risks. As a result of earlier failures in the 'decide-announce-defend' approach, contemporary nuclear decision-making is more attentive to stakeholder involvement. In countries with strong democratic traditions, the location of nuclear facilities is now made dependent on 'voluntary agreements' with the local communities concerned. But how voluntary are such 'voluntary agreements', when incomes and jobs in the candidate communities are often linked to nuclear facilities already established there? Schrader-Frechette [78] calls this the 'consent dilemma': those most able to give real informed consent (because they are not bound to the nuclear industry) are least likely to do so; those who have already been 'socialized' by the presence of the nuclear industry (through local benefits, employment opportunities, family ties to nuclear workers, etc.), and are thus least able to give free consent, are most likely to agree. Furthermore, such consent will always take place within the constraints of an agreeing context in the 'national interest' decided by central government.

Once again, the electricity future of the efficiency-renewable tandem assigns initiative and responsibility to local communities, and is itself dependent on local initiative and support. This stands in stark contrast to the electricity future based on nuclear power. Political preferences and choices regarding centralized authorities versus decentralized discretionary powers for citizens and communities will have a significant effect on the future of nuclear power.

8. Conclusion

This paper applied a 19-criterion framework to assess whether nuclear fission power can play a role in sustainable development. The framework applied was based on the four SD dimensions offered in the Brundtland report [79], alongside a fifth dimension, 'risk', which is particularly relevant when assessing nuclear programs. The results of this exercise are instructive, but can be extended with additional analysis, evidence and debate.

As regards planet, the incompatibility of nuclear expansion with electricity efficiency and full renewable power deployment largely overshadows the carbon-free steam generation by nuclear fission processes. The low-carbon chip is a bit attenuated when considering the life-cycle CO_{2eq} emissions of the nuclear fission cycle and its being embedded in a largely fossil fuel-driven energy economy. Such objections lose momentum, however, as the overall energy economy transition approaches an entirely carbon-free energy economy. Yet a carbon-free energy economy is itself highly dependent on the unrestricted deployment of energy efficiency and renewable energy, strategies that are impeded by nuclear expansion [12]. In this way, nuclear power acts as an obstruction to, rather than a driver of, the low-carbon energy economy. Additionally, nuclear fission plants hold the danger of causing irreversible damage to their embedding environments in the case of nuclear catastrophes (e.g. Chernobyl, Fukushima). The once-through fission cycle cannot expand its activities significantly because it will hit the limits of cheap uranium sources; its future depends on a fast transition to breeder plants in the second half of this century. Beyond paper and spin, the future of the breeder cycle remains unclear.

With regard to prosperity, nuclear fission power prices do not include all the present risks and long-term costs. Because nuclear power systems are plagued by serious doubts, eternal time horizons and likely irreversibility traps, it is virtually impossible to generate reliable cost numbers. There is one certainty, however: once a power plant is closed, only costs and risks remain, without benefits [80]. The only two nuclear reactors currently under construction in Europe are facing major overruns in investment expenses and construction time. Grübler [35] explains the facts as inverse learning effects in nuclear power plants. The capital investments and high technology intensity are not affordable by developing countries, limiting the nuclear option to industrialized and industrializing countries. Existing plants are facing challenges in security, reliability and vulnerability, to which they are responding only partially.

Regarding risks, nuclear power plants remain unable to obtain full indemnity insurance for catastrophic events underwritten by the global vested insurance and re-insurance companies. This proves that the best-informed experts consider the nuclear risks to be too high, higher than the significant income the companies could obtain from yearly nuclear risk premium payments. As a corollary, the IEA campaign for convincing citizens to accept nuclear risks is injurious. Nuclear plant owners are generally so closely linked to the societal power establishments that they can roll off the risks onto citizens and the future. In addition to civil power risks, there is also the risk of nuclear weaponry proliferation.

When assessing people's fortune, some of the evaluation criteria interact with criteria in the other groups. Delivery of affordable electricity to all people on earth is a major global concern, because it is a prerequisite for pursuing development. When its risks and future costs are neglected, we see that bulk nuclear power may be delivered at affordable expenses. However, when users of nuclear power pay the full costs and risks (though these are difficult to quantify precisely), the bills will go up, expectedly beyond economically acceptable limits. Furthermore, health and safety, and adherence to convivial living environments, are vital elements of wellbeing. When nuclear catastrophes happen, exposed populations lose out enormously and receive limited compensation. A catastrophe like Fukushima wreaks havoc on the electric power system and the overall energy economy, pushing the benefit/cost ratio of the nuclear enterprise down significantly. By impeding the fast transition to highly efficient and renewable low-carbon energy systems, nuclear power expansion prolongs the unsustainable lock-in, most detrimental to the earth's vulnerable climate.

In terms of politics, nuclear power decision-making is characterized by private and/or governmental technocracy, in which democratic steering and control take up a subordinate position. Since technocracy can capture its regulators, it can also manipulate deliberative forums and public engagement in order to endorse the incumbent policy rather than encouraging sustainable development policy. We highlight the need for a global independent agency to review nuclear power issues with a focus on society's best interests. This agency could also serve to qualify the nuclear regulatory institutions set up in various countries. The obvious difficulties associated with such an endeavor should not be ignored.

Today, neither the proponents nor opponents of nuclear power appear to be engaged in open scientific debate about the merits and potential role of nuclear power in a low-carbon energy future. Existing energy system transition forums have sidelined the nuclear question or accepted the superficial view of nuclear energy as a ready-to-use, highly productive low-carbon electricity source. This stance actually prolongs the attitude prevalent from the 1950s

to the 1970s, namely one of unfounded belief in the future success and technical solutions to intractable radiation and waste problems. Silencing alternative perspectives, analyses and positions is fatal to democratic decision-making; our exploration of the sustainability performance of nuclear fission power therefore seeks to challenge the dominant position of various vocal celebrities [81,82] and official institutions (IAEA, IEA, UK Government). Although the celebrities are renowned scientists, they are not expert in electric power systems analysis, neither in energy policy, nor in political economy, all disciplines helpful in the trying assessment whether nuclear power can be part of the future sustainable development.

References

[1] IEA. Energy technology perspectives 2012. Pathways to a clean energy system. Paris: International Energy Agency; 2012.
[2] IAEA. IAEA tools and methodologies for energy system planning and nuclear energy system assessments. Vienna: International Atomic Energy Agency; 2009.
[3] IAEA. Guidance for the application of an assessment methodology for innovative nuclear energy systems. INPRO manual. Vols. 1–9 of the final report phase 1 of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO). Vienna: International Atomic Energy Agency; 2008.
[4] UK Department of Energy and Climate Change (DECC). Appraisal of sustainability of the revised draft nuclear national policy statement: main report. London: UK DECC; 2010.
[5] UNEP. Rio declaration on environment and development. In: The United Nations conference on environment and development. Rio de Janeiro: United Nations Environment Programme; 3–14 June 1992.
[6] IPCC. Climate change 2007: synthesis report. Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. Geneva, Switzerland; Intergovernmental Panel on Climate Change; 2007. 104 p.
[7] Beerten J, Laes E, Meskens G, D′haeseleer W. Greenhouse gas emissions in the nuclear life cycle: a balanced appraisal. Energy Policy 2009;37:5056–68.
[8] Sovacool BK. Valuing the greenhouse gas emissions from nuclear power: a critical survey. Energy Policy 2008;36:2950–63.
[9] Fthenakis VM, Kim HC. Greenhouse-gas emissions from solar electric- and nuclear power: a lifecycle study. Energy Policy 2007;35:2549–57.
[10] van der Zwaan B. The role of nuclear power in mitigating emissions from electricity generation. Energy Strategy Rev 2013;1:296–301.
[11] Weisser D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 2007;32:1543–59.
[12] Verbruggen A. Renewable and nuclear power: a common future? Energy Policy 2008;36:4036–47.
[13] EPRI. Water use in electric power generation. EPRI report 1014026. Palo Alto, USA: Electric Power Research Institute; 2008.
[14] IPCC. Climate change and water. IPCC technical paper VI. Geneva: Intergovernmental Panel on Climate Change; 2008.
[15] IPCC. Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, NY, USA: Cambridge University Press; 2012.
[16] Barnaby F, Kemp J. Secure energy? Civil nuclear power, security and global warming. London: Oxford Research Group; 2007 〈http://www.oxfordresearchgroup.org.uk/publications/briefing_papers/secure_energy_civil_nuclear_power_security_and_global_warming〉.
[17] Eggermont G, Hugé J. Nuclear energy governance. SEPIA project. Brussels: Belgian Science Policy; 2011.
[18] Srinivasan TN, Rethinaraj TS. Fukushima and thereafter: reassessment of risks of nuclear power. Energy Policy 2013;52:726–36.
[19] OECD/NEA. Safety cases for deep geological disposal of radioactive waste – where do we stand? Paris: Organisation for Economic Co-operation and Development – Nuclear Energy Agency, Symposium Proceedings; 2008.
[20] IPCC. IPCC special report on renewable energy sources and climate change mitigation. Prepared by working group III of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press; 2012. 1075 p.
[21] Verbruggen A, Fischedick M, Moomaw W, Weir T, Nadaï A, Nilsson LJ, et al. Renewable energy costs, potentials, barriers: conceptual issues. Energy Policy 2010;38:850–61.
[22] IEA & OECD/NEA. Projected costs of generating electricity, 2010 edition. International Energy Agency, Organisation for Economic Co-operation and Development, Nuclear Energy Agency; 2010.
[23] OpenEI. Transparent cost database. US Department of Energy Open Energy Information Platform. Retrieved from 〈http://en.openei.org/apps/TCDB/〉 [accessed 02.12.13].
[24] Koplow DN. Nuclear power: still not viable without subsidies. Union of Concerned Scientists; 2011.
[25] Faure MG, Fiore K. An economic analysis of the nuclear liability subsidy. Pace Environ Law Rev 2009;26:419–50.
[26] Bradford P. The nuclear landscape. Nature 2012;483:151–2.
[27] Kaplan S. Power plants: characteristics and costs. Congressional research service report for congress; 2008.
[28] Bradford P. Taxpayer Financing for Nuclear Power: Precedents and Consequences. Working paper. Vermont Law School; 2008. Retrieved from 〈http://www.psr.org/nuclear-bailout/resources/taxpayer-financing-for.pdf〉.
[29] Junginger M, van Sark W, Faaij A. Technological learning in the energy sector: lessons for policy, industry and science. Cheltenham, UK: Edward Elgar Publishing; 2010.
[30] Ostwald PF, Reisdorf JB. Measurement of technology progress and capital cost for nuclear, coal-fired, and gas-fired power plants using the learning curve. Eng Process Econ 1979;4:435–54.
[31] Neij L. Cost development of future technologies for power generation—a study based on experience curves and complementary bottom-up assessments. Energy Policy 2008;36:2200–11.
[32] Williams RH. Toward cost buydown via learning-by-doing for environmental energy technologies. Review draft. Workshop on learning-by-doing in energy technologies. Washington: Resources for the Future; 2003.
[33] Kessides IN. Nuclear power and sustainable energy policy: promises and perils. World Bank Res Obs 2010;25:323–62.
[34] Kessides IN. The future of the nuclear industry reconsidered: risks, uncertainty and continued promise. Energy Policy 2012;48:185–208.
[35] Grübler A. The costs of the French nuclear scale-up: a case of negative learning-by-doing. Energy Policy 2010;38:5174–88.
[36] World Nuclear News. Flamanville costs up €2 billion. World Nuclear News; 2012. Retrieved from 〈http://www.world-nuclear-news.org/NNFlamanville_costs_up_2_billion_Euros-0412127.html〉 [accessed 17.04.13].
[37] Mez L. Nuclear energy – any solution for sustainability and climate protection? Energy Policy 2012;48:56–63.
[38] Les Echos. Areva remonte au front pour defendre l′EPR; 2012. Retrieved from 〈http://www.lesechos.fr/14/12/2012/LesEchos/21334-092-ECH_areva-remonteau-front-pour-defendre-l-epr.htm?texte=olkiluoto〉 [accessed 22.04.13].
[39] World Nuclear News. Olkiluoto 3 delayed beyond 2014; 2012. Retrieved from 〈http://www.world-nuclear-news.org/NN-Olkiluoto_3_delayed_beyond_2014-1707124.html〉 [accessed 17.04.12].
[40] IAEA PRIS. Country statistics – Sweden – Olkiluoto-3. International Atomic Energy Agency Power Reactor Information System; 2013. Retrieved from 〈http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=860〉 [accessed 17.04.13].
[41] Makhijani A, Boyd M. Small modular reactors. No solution for the cost, safety, and waste problems of nuclear power. Maryland/Washington: Institute for Energy and Environmental Research/Physicians for Social Responsibility; 2010.
[42] Csik BJ, Schenk K. Nuclear power in developing countries: requirements & constraints – a review of IAEA′s assistance to countries pursuing the nuclear option to help meet energy demands. Special reports. International Atomic Energy Agency Bulletin 2; 1987. p. 39–2.
[43] Rhodes R, Beller D. The need for nuclear power. Foreign Aff 2000;79:30–44.
[44] Jewell J. Ready for nuclear energy? An assessment of capacities and motivations for launching new national nuclear power programs Energy Policy 2011;39:1041–55.
[45] Goldemberg J. Nuclear energy in developing countries. Daedalus 2009;138:71–80.
[46] The World Bank. Gross domestic product ranking table 2011; 2011. Retrieved from 〈http://databank.worldbank.org/databank/download/GDP.pdf〉 [accessed 17.04.13].
[47] IAEA PRIS. Country statistics – Armenia – summary. International Atomic Energy Agency Power Reactor Information System; 2013. Retrieved from 〈http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=AM〉 [accessed 17.04.13].
[48] IAEA PRIS. World statistics – under construction statistics. International Atomic Energy Agency Power Reactor Information System; 2013. Retrieved from 〈http://www.iaea.org/PRIS/WorldStatistics/UnderConstructionReactorsByCountry.aspx〉 [accessed 17.04.13].
[49] Kruyt B, van Vuuren DP, de Vries HJM, Groenenberg H. Indicators for energy security. Energy Policy 2009;37:2166–81.
[50] IAEA PRIS. World statistics – life time energy availability. International Atomic Energy Agency Power Reactor Information System; 2013. Retrieved from 〈http://www.iaea.org/PRIS/WorldStatistics/LifeTimeEnergyAvailabilityFactor.aspx〉 [accessed 19.08.13].
[51] Lovins AB, Sheikh I, Merkevich A. Forget nuclear. Rocky Mount Inst Solutions 2008;24:24–7.
[52] Perrow C. Normal accidents: living with high-risk technologies. USA: Basic Books Inc.; 1984.
[53] Hirsch H, Becker O, Schneider M, Froggatt A. Nuclear reactor hazards. Ongoing dangers of operating nuclear technology in the 21st century. Report prepared for Greenpeace International, Amsterdam; 2005. 128 pp.
[54] NAIIC. The national diet of Japan – executive summary. The official report of The Fukushima Nuclear Accident Independent Investigation Commission, 2012. 88 pp.
[55] UK DECC. National policy statement for nuclear power generation (EN-6). London, UK: United Kingdom Department of Energy & Climate Change; 2011.
[56] Harremoës P, Gee D, MacGarvin M, Stirling A, Keys J, Wynne B, et al. Late lessons from early warnings: the precautionary principle 1896–2000. Environmental issue report 22. Copenhagen: European Environment Agency; 2001.

[57] Tyran J-R, Zweifel P. Environmental risk internalization through capital markets (ERICAM): the case of nuclear power. Int Rev Law Econ 1993; 13:431–44.
[58] Laes E, Meskens G, van der Sluijs JP. On the contribution of external cost calculations to energy system governance: the case of a potential large-scale nuclear accident. Energy Policy 2011;39:5664–73.
[59] Francis H. The insurance of nuclear installations. Prog Nucl Energy 1977;1: 63–71.
[60] Verbruggen A. Revocability and reversibility in societal decision-making. Ecol Econ 2013;85:20–7.
[61] Blowers A. Nuclear waste and landscapes of risk. Landscape Res 1999;24: 241–263.
[62] Blowers A. Why Fukushima is a moral issue? The need for an ethic for the future in the debate about the future of nuclear energy J Integrative Environ Sci 2011:73–80.
[63] Gillon L. De kwestie kernenergie: welke energie voor onze toekomst? Wat na Tsjernobyl? Scriptoria, Antwerp; 1986.
[64] Jasanoff S, Kim S-H. Containing the atom: sociotechnical imaginaries and nuclear power in the United States and South Korea. Minerva 2009;47: 119–46.
[65] Anderson K. The awareness principle: transparency and accountability in science and politics. Palgrave Macmillan; 2008.
[66] Namekata S. Interview: former U.S. nuke watchdog chair says regulators must stay independent. The Asahi Shimbun; 2013. Retrieved from ⟨http://ajw.asahi.com/article/0311disaster/fukushima/AJ201303140050⟩ [accessed 21.08.13].
[67] Winner L. The whale and the reactor. Chicago: University of Chicago Press; 1986.
[68] Grove-White R, Macnaghten P, Wynne B. Wising up: the public and new technologies. Lancaster: Institute for Environment, Philosophy and Public Policy (IEPPP); 2000. 44 pp.
[69] Rochlin J. Broken plowshare: system failure and the nuclear power industry. In: Summerton J, editor. Changing large technical systems. Boulder/San Francisco/Oxford: Westview Press; 1994. p. 231–61.
[70] IAEA. Stakeholder involvement throughout the life cycle of nuclear facilities. InternationalAtomic Energy Agency Nuclear Energy Series NG-T-1. Vienna, 2011.
[71] IAEA. Establishment of uranium mining and processing operations in the context of sustainable development. IAEA Nuclear Energy Series No. NF-T-1.1. Vienna: IAEA; 2009.
[72] Bergmans A, Elam M, Kos D. Wanting the unwanted: effects of public and stakeholder involvement in the long-term management of radioactive waste and the siting of repository facilities. Antwerp: University of Antwerp; 2008.
[73] OECD/IEA. Energy policies of IEA countries. Finland 2007 review. Organisation for Economic Co-operation and Development/International Energy Agency; 2008. 146 pp.
[74] ICRP. Application of the Commission′s recommendations for the protection of people in emergency exposure situations. ICRP Publication 109, International Commission on Radiation Protection; 2009.
[75] OECD/NEA. Stakeholders and radiological protection: lessons from chernobyl 20 years after. Organisation for Economic Co-operation and Development – Nuclear Energy Agency; 2006.
[76] Darst R, Dawson J. Waiting for the nuclear renaissance: exploring the nexus of expansion and disposal in Europe. Risks Hazards Crisis Public Policy 2010;1: 49–82.
[77] Blowers A, Sundqvist G, editors. Spec Issue J Integrative Environ Sci; 2010.
[78] Schrader-Frechette K. Ethical dilemmas and radioactive waste, a survey of the issues. Environ Ethics 1991:327–43.
[79] The World Commission on Environment and Development. Our common future. Oxford: Oxford University Press; 1987.
[80] Verbruggen A. Belgian nuclear power life extension and fuss about nuclear rents. Energy Policy 2013;60:91–7.
[81] World Nuclear News. Nuclear essential for climate stability. World Nuclear News; 2013. Retrieved from ⟨http://www.world-nuclear-news.org/EE-Nuclear-essential-for-climate-stability-0411137.html⟩ [accessed 04.11.13].
[82] Caldeira K, Emanuel K, Hansen J, Wigley T. To those influencing environmental policy but opposed to nuclear power. Public letter. Retrieved from ⟨https://plus.google.com/104173268819779064135/posts/Vs6Csiv1xYr⟩ [accessed 04.11.13].